Rocky Mountains Southwest Great Plains

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Temperature Gradient Weakening in Snow

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When snow of densities lower than about 250 kg/m³ metamorphoses under a temperature gradient, large crystals form, and the snow becomes weaker. These crystals form at selected sites as branch grains, because the local temperature gradient is increased at such sites. Calculations using a simple one-dimensional model of the process show that the geometrical relationships of the snow grains can explain the major features of temperature gradient metamorphism.

Keywords: Snow metamorphism, temperature gradient, depth hoar

Introduction

Temperature gradient snow (Sommerfeld and LaChapelle 1970) is involved in many avalanches. This fragile type of snow is made of large, distinctive crystals often called depth hoar (Seligman 1936, Yosida et al. 1955). Depth hoar was implicated in the formation of slab avalanches at least as early as Paulke (1932). Seligman (1936) first noted that depth hoar is the result of a temperature gradient across the snow. It is now known that a minimum gradient of 10° C per meter is necessary for depth hoar formation. What has not been known is the reason for the weakening associated with temperature gradient metamorphism and for the growth of very large crystals. Recent work (Sommerfeld 1983) has shown that previous theories were invalid because they ignored the complicated geometry of the ice lattice that makes up snow. They described the snow only in terms of average parameters—the density and average crystal size. The geometry of the ice lattice is now known to be very important in temperature gradient metamorphism.

The first person who attempted to quantify the ice network geometry was de Quervain (1973). He was able to quantify only very simple and regular geometries, although he recognized that more realistic, complicated geometries might be necessary to explain the process. Recent advances now make it possible to explain why the crystals grow large, why the snow becomes weak, and to quantify the process as far as its progress in time, increasing our understanding of an important factor in snow avalanche initiation.

Theory of Temperature Gradient Metamorphism

The dominant process in temperature gradient metamorphism is water vapor diffusion driven by the thermal gradient. The temperature gradient between different ice grains in the snow causes a vapor pressure gradient. The vapor flow rate is proportional to the vapor pressure gradient (Giddings and LaChapelle 1962) between the individual ice grains. Because the flow law is so simple, it would seem to be simple to calculate the progress of the metamorphism. However, no one has been able to calculate the growth rate of the crystals, for example, without making very unrealistic assumptions. Also, no one has been able to explain the drastic weakening that is associated with this type of metamorphism. It is now known that the difficulty is caused by the complicated geometry of the ice network that makes up snow.

An examination of figure 1, a representation of a simplified snow like those tacitly assumed in previous theories, shows the problem. All spacings are the average spacing and all sizes are the average size. The problem comes in trying to explain the crystal growth. If a temperature gradient is put across the snow in figure 1, nothing much happens to the grain size. The grain labeled C has the average gradient above and below it. The growth rate is determined by the vapor flow to and

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from the grain, and it receives as much water vapor from below as it loses from above. Therefore, it does not change size. The curvature in the flow rate-temperature relationship and considerations of surface energy would make the grain increase in size gradually, but the growth rate would be much too small to account for the observed growth rate (Giddings and LaChapelle 1962, Perla 1978, Colbeck 1980).

To understand what's missing, a more realistic picture of snow is needed. Three important types of snow grains have been identified—link grains, chain grains, and branch grains (Kry 1975, Gubler 1978). The simplified snow shown in figure 1 has chain grains (C) and link grains (L), but not branch grains. Suppose one branch grain (B) is added, as in figure 2. To understand the difference that the one branch grain makes, one must know that the thermal conductivity of ice is 100 times that of air. Therefore, the temperature of the bottom of the branch grain (B) is within 1% of the temperature at the top. The distance between the branch grain and the grain below it is about one-half the average distance between grains. The thermal gradient between the branch grain and the grain below is:

$$\frac{dT}{dZ} = \frac{T_B - T_C}{Z_B - Z_C},$$

where T is the temperature, Z is the vertical position, and B and C refer to the grains in figure 2. In figure 2, dT/dZ for the branch grain is twice the average because $Z_B - Z_C$ is one-half the average. Because the growth rate is approximately proportional to the thermal gradient, the branch grain (B) grows at twice the average rate at the bottom. To do this, it robs water vapor from the grain below.

Figure 2 is still not very realistic. Figure 3 gives a better approximation of real snow and shows the three types of grains more clearly.

An important difference between chain and link grains on the one hand, and branch grains on the other, is that the first two types of grains participate in the interconnecting ice network that gives cohesion to snow, while branch grains do not. The branch grains have only one bond each, hang in space, and contribute nothing to the strength. If branch grains grow at the expense of chain and link grains in a given snow, that snow becomes weaker. Furthermore, there are fewer branch grains in suitable growth positions than there are total grains. Because only the branch grains grow, the snow ends up with fewer grains, and the branch grains grow to much larger sizes. The inclusion of branch grains in the model explains the two major features of temperature gradient metamorphism—the growth of large crystals and the severe weakening.

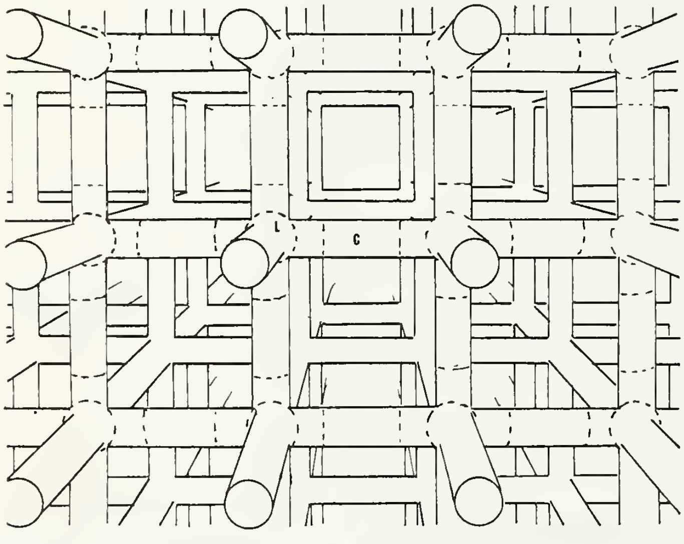

Figure 1.—Idealized snow where all grains are the average size and all spacings are the average spacing.

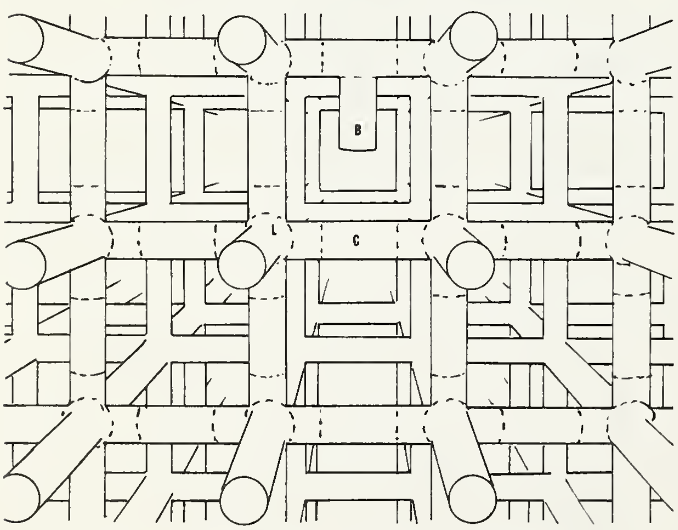

Figure 2.—Idealized snow with one branch grain.

Theoretical Analysis

Because snow is a complicated three-dimensional network of ice grains, measuring the exact geometry of a snow sample is probably impossible. To verify the branch grain theory presented above, it is necessary to simplify the problem to the point that meaningful measurements can be made. The main assumption is that the process is strictly in one dimension. That is, the vapor only flows in the Z direction with no component in the X or Y direction. This single assumption greatly simplifies the analysis because the necessary information can be obtained from two-dimensional thin sections of snow. For example, consider any vertical plane section through the simplified snow and suppose that instead of a single branch grain, it had about 10% of the total number of grains as branch grains and that they were randomly placed in the regular ice lattice. That section might look like figure 4. It would be impossible to deduce the three-dimensional shapes of the ice lattice only from this section but, because of the assumption, that is not necessary. Only the vertical paths of water vapor are important and, if the section is random and large enough, the lengths of those paths are adequately sampled by the thin section. Because the local temperature gradient depends mainly on grain spacing, this should

be enough information to calculate the grain growth rates, at least to a good approximation. To do this, a mathematical expression for the grain growth rates is needed, and because of the large numbers of grains, a distribution of growth rates which depends on the distribution of spacings is also needed. The growth rate depends on the vapor flow to and from the grains and the necessary equations can be derived from the basic

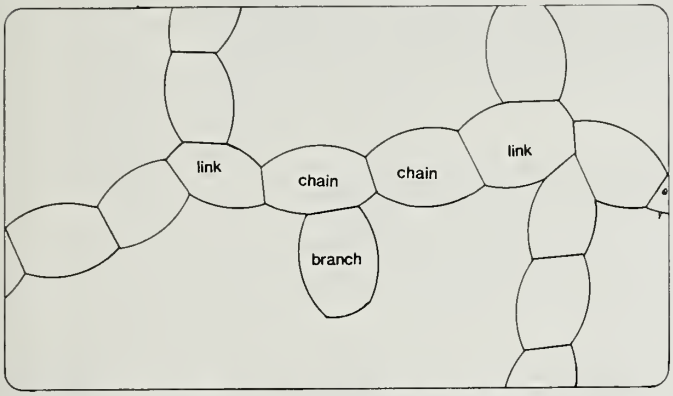

Figure 3.—A more realistic two-dimensional representation of snow, showing the three major types of snow grains.

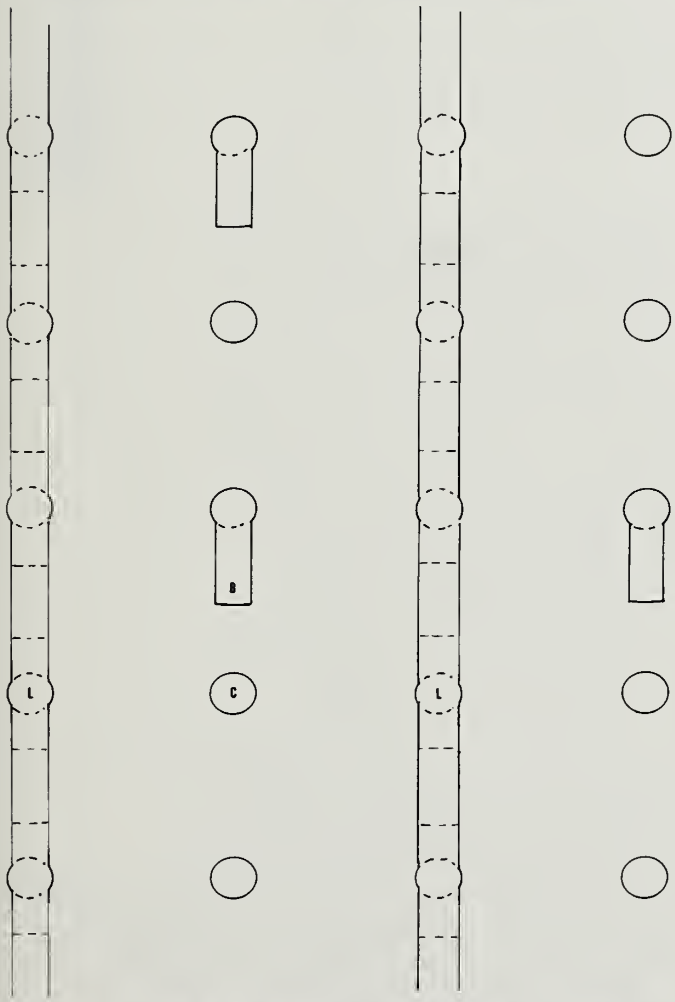

Figure 4.—Vertical thin section through idealized snow which has randomly distributed branch grains.

flow rate equation and measurements of the temperaure gradient and the grain spacing. Detailed derivations are presented in Sommerfeld (1983) and will not be repeated here.

Experimental Verification

Evidence that the branch grain theory is correct is obtained by observing the shape of well-developed temperature gradient grains (fig. 5, and Colbeck 1983). Temperature gradient grains are approximately bell-shaped, attached at the narrow top and free at the wide bottom: that is, they are large branch grains in the optimum growth orientation. Their shape shows they grow on the bottom and sublimate at the top. It has been erroneously reported that the outsides of temperature gradient grains are stepped (Eugster 1952). Generally, the insides and bottoms are stepped while the outsides are smooth, except perhaps at the very top. Growing ice crystals exhibit facets and steps, while sublimating ice crystals are rounded (Hobbs 1974). Notice that the grains in figure 5 have flat facets, steps, and relatively sharp corners on their bottoms and on the insides of the hollow grains while the tops show more rounding. Also, there is a tendency toward wider bottoms and narrower tops in many of the grains. This tendency has been observed frequently (Eugster 1952, Sommerfeld and LaChapelle 1970, de Quervain 1973) and is even more apparent when this type of grain is examined in three dimensions. In some cases it appears that the interior roughness has become exposed by the upper surface sublimating away. This seems to be the case in the right-hand side of the largest grain, upper center, in figure 5.

Although a test of the theory can be made from thin section data, some severe assumptions must be made. A set of experiments was performed and samples taken nine times during a 28-day period (Sommerfeld 1983). The experiment is summarized in table 1 and figure 6. Grain lengths and grain spacings were measured from thin sections. The measured length and spacing distributions were used in calculations based on an equation that predicted future distributions.

For the series labeled A in table 1 and figure 6, the distributions of the preceding measurement were used as the starting point for the calculations. The series labeled B used the previously calculated grain length distribution as a starting point. Thus, series B is a more severe test of the theory. The theory holds up fairly well, considering the assumptions. The mean grain sizes are calculated well within measurement error, even for series B. The medians are not calculated to as good an accuracy, and this is reflected in the differences between the measured and calculated curves shown in figure 6. Previous theories have not been able to calculate the mean grain sizes within a factor of 5 without very unrealistic assumptions. This theory represents a considerable improvement over previous theories, but it also could be improved by less severe and more realistic assumptions about the geometry.

More evidence that the bonding decreases as predicted by the theory comes from accurate measure-

ments of the thermal gradient which were performed at five levels in the sample (fig. 7). De Quervain (1973) estimated that about half the thermal conductivity in snow results from the vapor transport. Because the vapor pressure is higher in the warmer snow at the bottom, the vapor transport is higher and the thermal conductivity is higher at the bottom than at the top. Notice the slight curvature in the slope in figure 7. During the first half of the experiment the slope is concave; that is, it becomes progressively steeper as it rises to colder temperatures. With a constant heat flow, the temperature difference across any layer is inversely proportional to the thermal conductivity. The higher thermal conductivity at the bottom gives a lower temperature difference, resulting in the concave slope. At day 16 the slope between 0 and 15 cm becomes planar while above that level it remains concave. With increasing time it changes to convex across these layers. This can only occur through a decrease in the thermal conductivity at the lower levels. Because the thermal conductivity due to vapor transport remains the same, the thermal conductivity of the ice network must be decreasing. A decrease in the ice conductivity would be the result of a decrease in bonds, a decrease in the number of chain and link grains, and an increase in the number of branch grains. Such a change in the relative numbers of different types of grains would also result in a decrease of strength.

Figure 5.—Thin section through a sample of real snow after 25 days of 30° C per meter temperature gradient.

Summary

The branch grain theory states that temperature gradient metamorphism proceeds through the growth of branch grains because branch grains are in the most favorable geometry for growth. Agreement between measurements of snow thin sections, theoretical calculations, and grain morphology provide strong support for this theory. Since branch grains do not contribute to either the strength or the ice network conductivity, the theory explains both the severe weakening and the decrease in thermal conductivity during temperature gradient metamorphism (Bradley et al. 1977). The growth of large grains is also explained by this theory because only part of the grains are in the ideal growth position. As the process goes on, the branch grains acquire most of the water mass and therefore must grow to much larger sizes than the original grains.

Two serious assumptions were made to test the theory: (1) the process is strictly one-dimensional, and (2) the spacings above and below the grains are statistically independent. The first assumption is an approximation—an examination of the thin sections shows that the

Table 1.—Grain size distribution, area ratio = 8.0, growth site fraction = 0.10

TG	II	III	IV	V	VI	VII	VIII	IX
Temperature gradient	0.30	0.38	0.38	0.38	0.38	0.36	0.36	0.36
Time (days)	3	6	10	12	17	20	26	28
Measured								
Mean	.22	.24	.27	.27	.30	.30	.30	.31
Median	.14	.16	.17	.17	.19	.18	.18	.18
Grain fraction[1]	.84	.80	.78	.72	.54	.55	.50	.54
A[2]								
Mean	.21	.24	.27	.29	.32	.33	.35	.33
Median	.15	.17	.20	.20	.23	.23	.24	.21
Grain fraction	.89	.75	.69	.72	.62	.49	.47	.47
B[3]								
Mean	.21	.23	.26	.27	.29	.31	.33	.33
Median	.15	.18	.20	.22	.24	.25	.27	.28
Grain fraction	.89	.81	.73	.70	.65	.62	.58	.57

[1]*Fraction of the original grains remaining.*
[2]*Calculated from experimental distributions.*
[3]*Calculated from last calculations.*

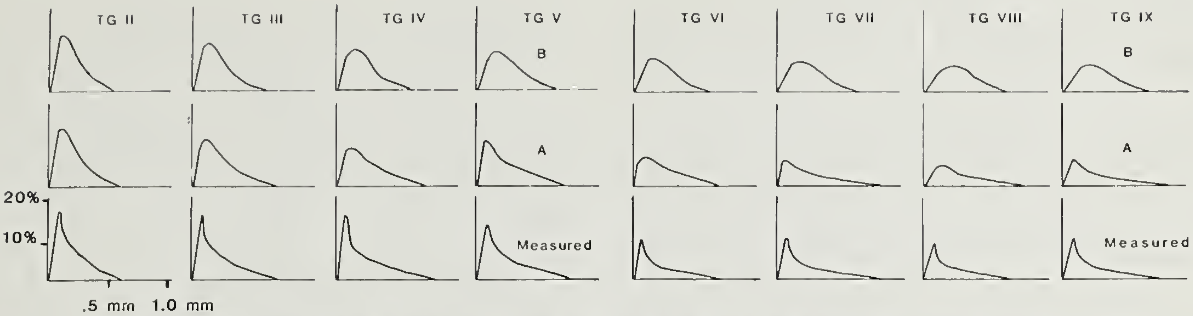

Figure 6.—A comparison of measured and modeled grain size dis tributions. "A" is adjusted back to the measured distribution for each succeeding stage. "B" is calculated from the initial distribution without adjustment.

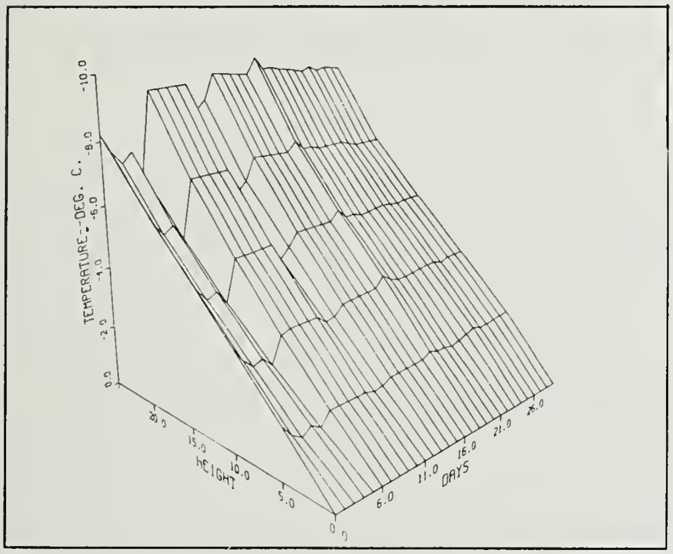

Figure 7.—Temperature profile in a 30 cm high sample at different days.

grains grow sideways as well as down, although their downward growth predominates. The second assumption is probably true at the start, but must become less true as the grains with small spacings below and large spacings above grow at the expense of other grains. The general agreement between the experiment and the calculations shows that the major features of temperature gradient metamorphism are explained by the branch grain theory. The shortcomings are not inherent in the theory, but in our inability to make the required measurements of the complicated geometry at the present. Still, the theory is useful in calculating the progress of temperature gradient metamorphism and it shows that the process can be understood in fairly simple terms.

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